Remote Sensing of Vertical IOP Structure

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LONG-TERM GOALS

The long-term goal of this project is to determine under what optical conditions the vertical structure of inherent optical properties (IOP) can be obtained from remote sensing.

SCIENTIFIC OBJECTIVES

This work includes developing a two-flow model to evaluate the conditions under which subsurface optical structure is detectable, and to develop an inversion model to determine the vertical structure of the IOP based on the presence of horizontal gradients in the spectral reflectance. We are also examining the role of the volume scattering function in determining the measured reflectance.

APPROACH

The components of our approach are:

1. Evaluate the conditions under which subsurface optical structure is detectable,
2. Develop an inversion model to determine the vertical structure of the IOP based on the presence of horizontal gradients in the spectral reflectance,
3. Examine the effects of changes in the volume scattering function on the reflectance,
4. Evaluate the model using field data.

An analytical model was developed to examine the conditions that subsurface optical structure may be detectable. We will use measurements collected during the field experiments at the LEO-15 site to test models for inverting to get optical structure. Data collected during the field experiments includes several measures of the volume scattering function under a wide range of conditions. These

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14. ABSTRACT
The long-term goal of this project is to determine under what optical conditions the vertical structure of inherent optical properties (IOP) can be obtained from remote sensing.

15. SUBJECT TERMS

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measurements will be used to examine if the volume scattering function is important in determining the reflectance under single-scattering conditions.

The ability to use remotely sensed radiance to determine vertical structure depends on the optical properties and thickness of the surface mixing-layer (ML). In this region the physical processes are assumed to mix particles and dissolved materials faster than source or sink terms for the given material, which gives rise to a layer in which the optical properties can be assumed to be homogeneous. Such a surface mixing layer is formed by the action of wind, waves and convection.

Light penetration through the surface layer depends on the optical properties of the surface layer and its thickness. To be detectable, stratification in optical properties must exist within the satellite viewing depth and there must be sufficient contrast between the surface layer and those beneath it. Since $R_{rs} \propto \frac{b_b}{a_t}$, no contrast will exist if both the backscattering (b_b) and total absorption (a_t) change by the same proportion between the surface and lower layers. It can be shown that the solution to the radiative transfer equation at a fixed optical depth (such as in the case of water leaving radiance) will remain constant if the IOP co-vary (i.e. a/b, a/c, b/c are constant) and the shape of the phase function is constant. We will refer to cases where the optical properties co-vary, as being vertically optically homogeneous because an equivalent homogeneous distribution of IOP exists that would provide the same reflectance. Optical homogeneity in the vertical requires that both the backscattering and total absorption increase by the same proportion, which is more likely to occur at shorter wavelengths. This is because the total absorption coefficient is dependent on the contributions by water, CDOM, and particles (phytoplankton, detritus, and sediment) and in coastal waters particles alone dominate b_b. For both b_b and a_t to change by the same proportion the optical properties must be dominated by the particles. In the red portion of the spectrum water has a large absorption coefficient and it is therefore less likely that particles will dominate the optical properties. Thus it is most likely that vertical optical homogenity will affect only a part of the spectrum.

To quantify the conditions under which we expect the spectral reflectance to be influenced by the vertical structure of the IOP we will perform a sensitivity analysis. We will start by assuming a simple two-layered system of turbid and clear water such as may be found in a river plume (turbid over clear) and over a continental shelf (clear over turbid). We will combine the structure with assumed spectral shapes for the absorption and scattering by CDOM, phytoplankton, detritus, and sediments as input into a radiative transfer model. The radiative transfer model will then be used to study the change in the remotely sensed reflectance as a function of surface and subsurface layer composition, thickness of the surface layer, optical gradient between layers, and wavelength. This study will be useful in determining at which wavelengths the R_{rs} is most likely to be influenced by subsurface structure given the vertical distribution of optical properties. We have recently used a similar approach to study the effect of the presence of thin layers on remotely sensed reflectance (Petrenko et al, 1998). A rigorous error analysis study will determine the sufficient contrast needed for the lower layer to be detectable.

WORK COMPLETED

We have developed an analytical two-flow model with a two layer stratification in IOP to establish the sensitivity of the irradiance reflectance (R(0-)=E_u(0-)/E_d(0-)) to the contrast in the layers IOP and the mixed layer depth. The model is a standard two-flow model with downwelling irradiance

partitioned into direct and diffuse components. We elected to use Haltrin's closure (Haltrin 1999 and references therein), which approximate the phase function by a delta function in the forward direction plus an isotropic diffuse component. This model and results obtained using it were presented at the Ocean Science conference (Carlstrom, 2000).

We have completed 2 studies of field measurements in which vertical structure was evident in ocean color imagery. One study was an analysis of images collected off Oceanside California during the Littoral Optics Experiment. Internal waves were evident in color imagery on two occasions. The characteristics of the waves inferred from the imagery were consistent with in-water observations (Weidemann et al, 2000). The second study utilized hyperspectral imagery collected in East Sound, Washington using the NRL's Phills sensor. A hydraulic jump over the sill at the entrance to the sound is evident in the images. Even though the imaging system was uncalibrated we were able to estimate the height of the internal waves as a function of position.

We have completed two field campaigns at the LEO-15 site. In the summer of 2000 we concentrated our measurements close to shore where the surface waters were very turbid. Data from this cruise is available from our anonymous ftp site at photon.oce.orst.edu. In the summer of 2001 we focused our efforts further offshore where clear over turbid conditions prevailed. We were also able to sample a wide range of optical water types at stations running from the LEO nodes to the shelf break.

RESULTS

Comparisons between Haltrin's model and hydrolight indicate the analytic solution is only valid in very clear water cases. The model work did indicate that the surface reflectance is linearly dependent on the ratio of b_b/a between layers (ρ) and exponentially with the depth of the layer interface. We also found that the contrast in reflectance caused by the vertical structure is nearly independent of the incoming light distribution and the angle of the sun.

Using the data collected during the 2000 experiment we compared the backscattering measured using a hydroscat, eco-vsf, and a volume scattering function meter (Pegau et al., 2001). The instruments gave results that were in good agreement even in the very turbid water and there was no evidence of an environmental variable that effected the agreement. This was a very satisfying result given the differences in angular resolution and calibration approaches. Using the backscattering coefficient it was then possible to trace water masses using the backscattering ratio $\left(\frac{b_b}{b}\right)$ that showed resuspended materials being carried offshore where the particles formed an intermediate nepheloid layer (Figure 1). Our analysis of the backscattering coefficient measurement has led to an improved algorithm for estimating the backscattering coefficient from the measurement of scattering at a single angle. By separating the scattering by water and particles we can improve our estimate of the backscattering coefficient of the system (Boss and Pegau, 2001).

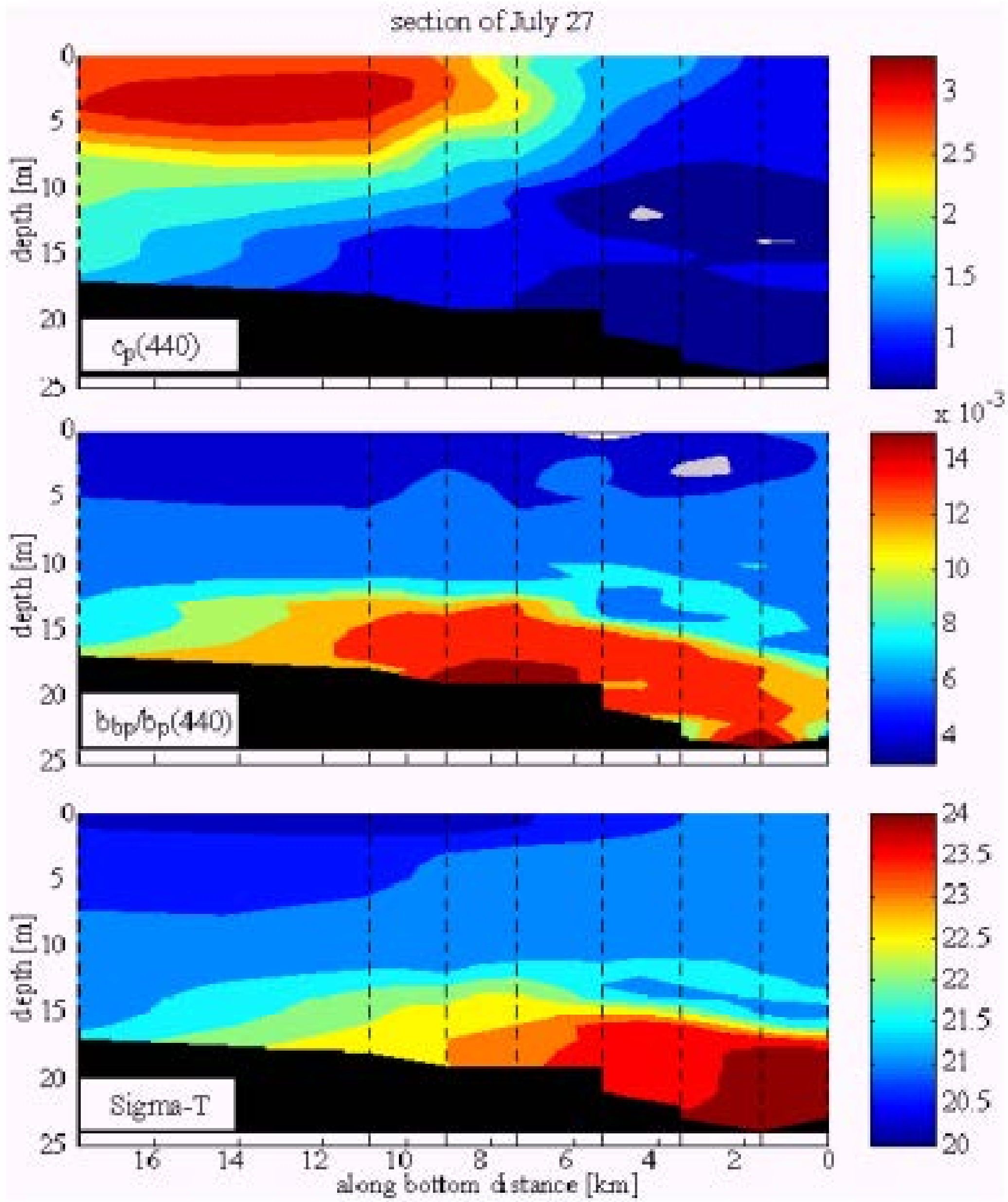

Figure 1. A across shelf transect along the a-line at the LEO-15 site showed an intermediate nepheloid layer at the offshore stations at 15 m depth. The backscattering ratio and density profiles indicate that the source of particles is closer to shore than would be inferred from the beam attenuation profiles.

Analysis of images that included internal waves indicates that internal structure in optical properties can be inferred from uncalibrated sensors. In data from East Sound the image shows the pattern of a hydraulic jump associated with tidal flow over a sill. Characteristics of the waves like group speed, wavelength, and amplitude can be determined from the optical data. Figure 2 includes the change in interface height along 4 lines as estimated by the reflectance. A detailed description of the internal wave structure can be found in Barnard (2000). Analysis of the changes in reflectance caused by

solitary waves off the coast of California showed that the group speed and wavelength could be determined from low spectral resolution measurements (Weidemann et al., 2001)

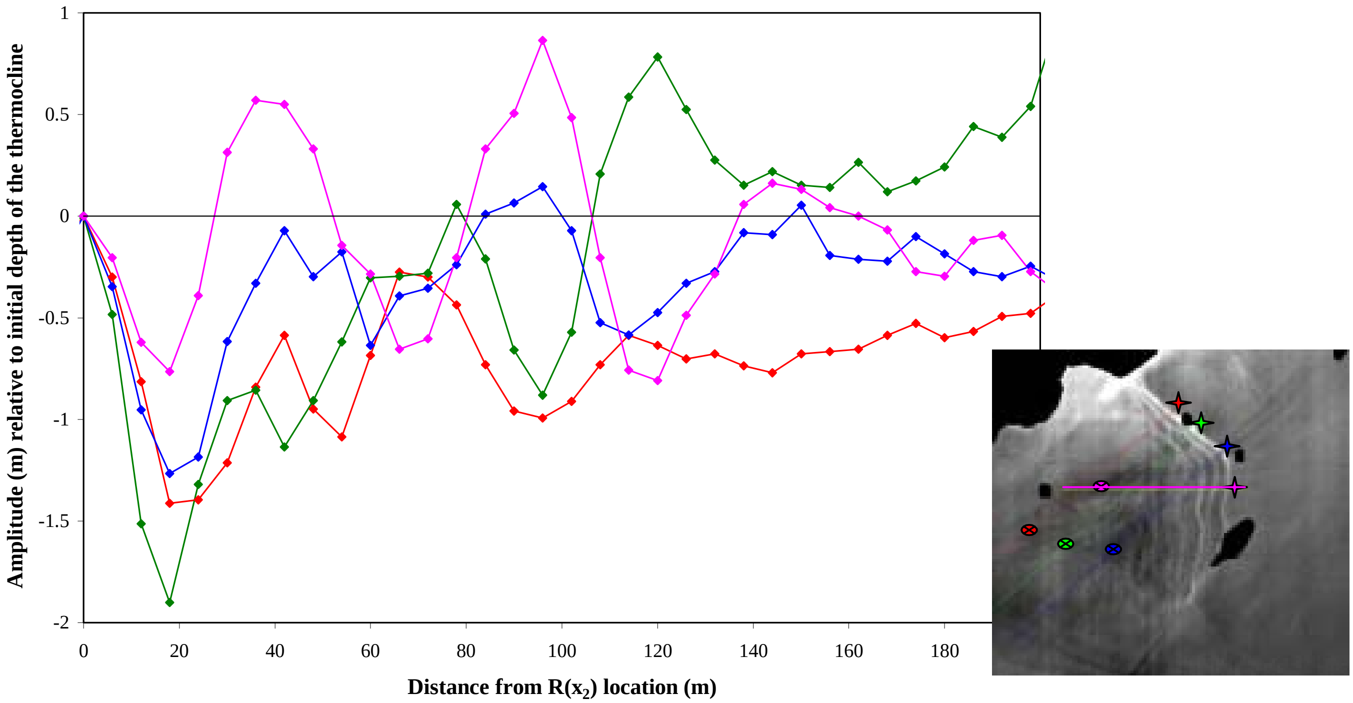

Figure 2. The amplitude of the internal wave pattern estimated along four lines across the banded feature seen in the inset. Near the sill the waves appear to be topographically locked, but past the end of the sill the waves are freely propagating.

IMPACT/APPLICATIONS

Providing information on the vertical distribution of IOP will enable more exact inversion of ocean color to optically active water constituents. The contrast in reflectance is not a strong function of the light field so the ability to detect subsurface structure is primarily dependent on the depth and optical properties of the layer. Techniques for measuring the backscattering coefficient are in good agreement, however new algorithms for the processing of backscattering measurements can improve our measurement of the backscattering coefficient.

TRANSITIONS

Data collected during the summer of 2000 is available to all investigators at our anonymous ftp site. The IOP and AOP data collected during 2000 at the LEO-15 site has been used by Curt Mobley at Sequoia Scientific to model the effect of the VSF on closure (Mobley et al., 2001). The same IOP data was used by our Ukranian collaborators (Micheal Lee et al., MHI) to do attenuation corrections to their VSF measurements.

RELATED PROJECTS

None

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PATENTS

None